Summary

The number of hazardous waste sites across the United States has grown to approximately 217,000, with billions of cubic yards of soil, sediment, and groundwater plumes requiring remediation. Contamination at these sites ranges from relatively easy-to-clean petroleum hydrocarbon spills to complex multicomponent, multiphase, heterogeneous subsurface solute masses resulting from a variety of past industrial and commercial practices. Sites contaminated with more recalcitrant contaminants or with more complex hydrogeologic features have proved to be a significant challenge on every level—technological, financial, legal, and sociopolitical.

Like many federal agencies, the Navy is a responsible party with a large liability in hazardous waste sites. The Navy's Environmental Restoration Program encompasses a wide array of contaminants reflecting the military's multiple purposes over the past 100 years as well as a diversity of locations, including coastal environments and inland waterways. Because efforts to remediate hazardous waste sites began as much as 20 years ago, a large percentage of identified hazardous waste sites have reached the latter stages of cleanup (i.e., beyond remedy selection). As the Navy plans completion of the Environmental Restoration Program, several unresolved remediation issues have become evident. Most important, conventional remediation technologies such as pump-and-treat have been shown to be inadequate in meeting drinking-water-level cleanup standards for many of the complex sites typical of Navy facilities (NRC, 1994). For certain treatment technologies, it has often been observed that the removal rate of contaminant mass tends to decline over time to the point where further expenditure of resources appears to

achieve little or no additional mass reduction. In many cases it is not clear how to change or terminate remedies that have proved ineffective or how to change cleanup goals.

To obtain advice in overcoming these obstacles, the Navy requested the National Research Council to study issues associated with the latter stages of remediation of contaminated soil, sediment, and groundwater at Navy facilities. In particular, the committee that was formed was asked to evaluate the unique technological and regulatory problems present at those sites for which chosen remedies have been in place but for which cleanup goals have not been met. The following specific tasks were given:

- define a decision-making framework that is embodied within a "systems engineering approach" to site cleanup,
- review innovative technologies for cleanup of groundwater, sediment, and soils, focusing on the top technologies that should be considered for the three or four greatest Navy problems,
- consider how remedies can be altered over time to introduce innovative technologies where the chosen remedy is no longer optimal because of changing site conditions, limited efficacy of technologies, or the discovery of new contamination and/or exposure pathways, and
- define logical endpoints and milestones for site closure.

In response, this report proposes a comprehensive and flexible approach, referred to as "adaptive site management," for dealing with difficult-to-remediate hazardous waste sites over the long term. Although adaptive site management is entirely consistent with the current cleanup paradigm used at federal facilities (as principally defined by Superfund), it has additional features that stress knowledge generation and transmittal and that complement more traditional cleanup objectives in order for progress to be made at sites where recalcitrant contamination prevents site closure and subsequent unrestricted land use.

Adaptive site management is responsive to the concern of large responsible parties that current technologies have proved to be ineffective in reaching cleanup goals for many types of contamination. Many studies and reports have documented that there are still no proven technologies for addressing hydrogeologically complex sites contaminated with dense nonaqueous phase liquids (DNAPLs) and metals, which are the contaminants of concern at many federal facilities. A variety of technical factors—such as geological and flow heterogeneity as well as slow mass transfer from solid phases and free phase contamination—limit remediation effectiveness and lead to the "asymptote" effect where further operation of the remediation system does not significantly reduce contaminant levels. At the present time, there is very limited regulatory or policy guidance on what to do when the asymptote is reached before cleanup goals have been met as long as the remedy remains protective of human health and the environment. The goals of adaptive site management are to facilitate decision making when the effectiveness of the remedy reaches an asymptote prior to reaching the cleanup goal and, if necessary, to facilitate implementation of long-term stewardship (long-term management in DoD terminology). This approach can accommodate different cleanup objectives, it provides guidance at key decision-making points, and it is a mechanism for dealing with the uncertainty inherent in many remedial strategies—both engineered technologies and institutional controls.

ADAPTIVE SITE MANAGEMENT DESCRIBED

The predominant paradigm for site restoration in the United States has until relatively recently involved a highly linear, unidirectional march from site investigation to remedial action and eventually to site closure. However, as sites have advanced through the restoration process and the need for site management over the long term has in many cases become apparent, there has been a growing recognition that a more iterative approach is needed. Thus, this report advocates a broad systems approach that promotes effective knowledge generation (monitoring and fundamental research) and use of that knowledge to provide a wider range of decision options and thereby improve overall site management. These characteristics are embodied in the concept of adaptive management—an approach to resource management in which policies are implemented with the express recognition that the response of the system is uncertain, but with the intent that this response will be monitored, interpreted, and used to adjust programs in an iterative manner, leading to ongoing improvements in knowledge and performance. The committee has coined the term "adaptive *site* management" (ASM) to refer to the application of the adaptive management concept to hazardous waste cleanup.

Within the environmental arena, adaptive management concepts are timely, given the observed limitations in remediation effectiveness and the increased use of remedies like containment and institutional controls that will leave residual contamination in place for long periods. To date, the principal use of adaptive management has been for applications to wildlife and ecosystem management, water resources planning, and global climate change assessment. However, the concept of adaptation is not foreign to hazardous waste cleanup, and there are certainly cases where project managers have modified remedial activities in response to poor system performance. Over the last decade, a number of formal approaches have been developed to introduce adaptation specifically into data collection and site characterization activities, although adaptive management has not yet been incorporated into the remedial design and implementation process as a whole.

ASM formalizes questions and decisions that the remedial project manager and remediation team should address and reach consensus on to readily adapt to changes in technology, remedy effectiveness, and other external influences that impact the management of contaminated sites. The main tenets of ASM are that it:

- is applicable at various stages of site restoration,
- is applicable to a wide variety of sites regardless of the contaminants being addressed or remedies envisioned,
- provides a mechanism for the optimization of existing remedies, changing ineffective remedies, and refining the site conceptual model,
- formalizes the routine examination of monitoring data and how to act upon the data,
- incorporates public participation,
- recognizes uncertainty and suggests approaches to dealing with it, especially when institutional controls are used,
- stimulates the search for new, innovative technologies to replace older or inefficient approaches,
- stresses the need for pilot programs to test both new technologies as well as modifications of existing technologies that might enhance their effectiveness, and
- recognizes the increasing role of long-term stewardship.

ASM encompasses the initial steps of site management, including the site conceptual model and risk assessment. Additional detail on these steps is provided in Chapter 2. This summary, however, focuses on the latter stages of ASM: remedy selection and implementation, monitoring remedy performance, adapting the remedy or management goals to accommodate changing conditions and improve cost-effectiveness, and completing the remedy and closing out the site. Figure S-1 shows the latter stages of ASM, which is characterized by management decision periods (MDP) designed to take advantage of the feedback loops embedded in ASM, such that uncertainties in site restoration can be addressed. These MDPs are also formal opportunities for the remedial project manager and other project managers, regulators, and interested stakeholders to evaluate incoming and existing data to determine if the remedial technology is meeting its objectives and, if not, to reach agreement on what additional management steps need to be taken. These decisions would take into account pilot-scale work, changes in land use or stakeholder needs, improvements in analytical resolution which might point to the presence of additional contaminants, and monitoring data and other intelligence that may lead the remedial project manager to refine and/or revise a management decision.

The purpose of the first decision period, MDP1, is to ensure that the remedy selected is practicable and implementable under site-specific conditions and that an appropriate, well-designed monitoring plan is developed. This can be important where there has been a long lag time (years) between remedy selection and implementation such that initial assumptions may no longer be valid. Subsequent to MDP1 and once the remedy is implemented, several actions can potentially occur as part of ASM. Along with operation of the remedy, there are ongoing monitoring activities. Several performance-related questions—lumped under MDP2—characterize this phase of cleanup.

Denoted alongside remedy implementation in Figure S-1 is evaluation and experimentation—an activity unique to ASM and one of the hallmarks of adaptive management in general. It refers to the conducting of experiments and other research activities in parallel with implementation of the chosen remedy. This activity occurs ideally at the level of an individual site, in which portions of the site are devoted to experimentation while others are undergoing the chosen remedy, although it may refer to collecting information about experiments going on elsewhere, the results of which are relevant to specific sites. The evaluation and experimentation track is an opportunity to test innovative, less certain, sometimes riskier remedies that were not well enough established to be chosen as the initial remedy in the Record of Decision (ROD).

Later management decision periods give remedial project managers an opportunity to use information gained during evaluation and experimentation and routine monitoring to optimize the existing remedy, change the remedy, or even change the remedial goal. Depending on the action chosen, MDP3 may lead back to the initial steps of site management, remedy selection, or remedy redesign. MDP3 is a critical juncture

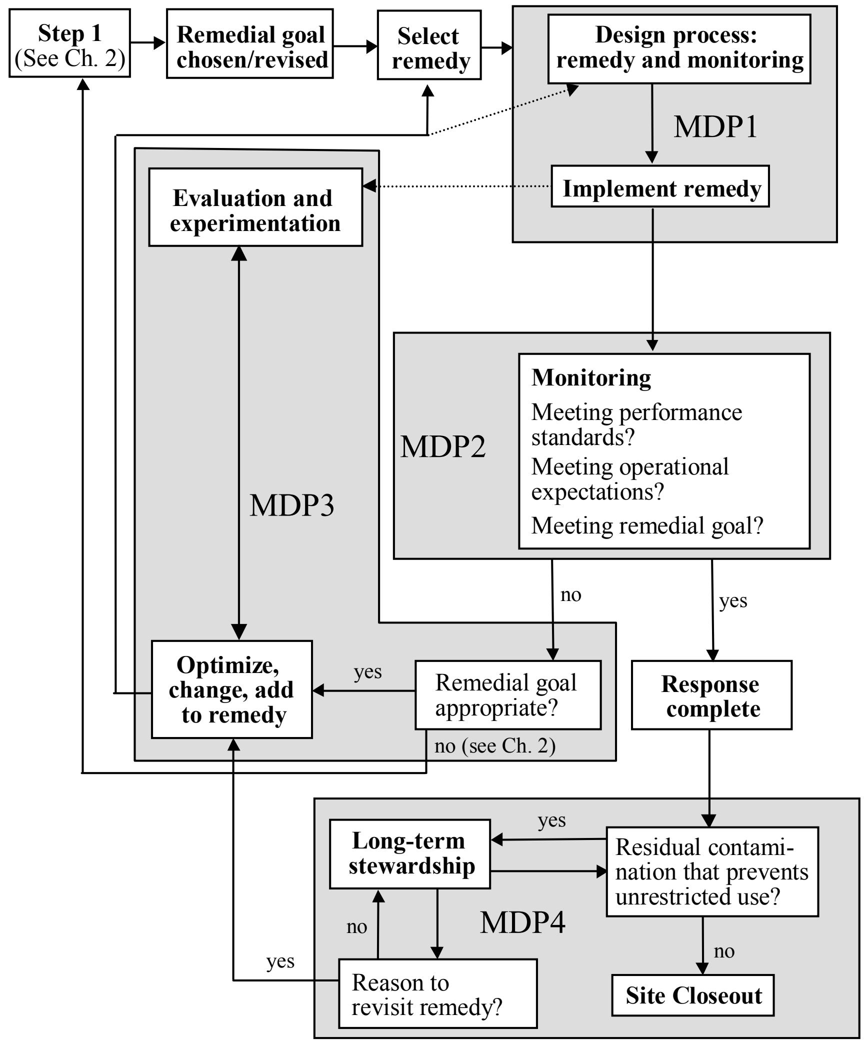

FIGURE S-1 Latter stages of adaptive site management: post-remedy selection. The shaded areas show the activities related to the management decision periods described in the text.

at which many current sites are stalled because of lack of information about alternatives and the absence of any regulatory incentive to change course.

The final major decision of adaptive site management is MDP4, during which sites with residual contamination levels above cleanup goals are periodically assessed. Like MDP3, this decision can lead to a change in remedy if it is found that alternative technologies exist that can help achieve cleanup goals. This also presents a departure from the current cleanup paradigm because the five-year review process that characterizes long-term stewardship does not support changing remedies unless the existing remedy is not protective of human health and the environment. When site managers, regulators, and the affected public have agreed that there are no unacceptable levels of contaminants left in place (i.e., the use is unrestricted), site closeout can proceed—the last step of ASM.

The following sections discuss different components of ASM in greater detail and provide key conclusions and recommendations. They correspond roughly to the organization of Chapters 3 through 6.

MONITORING AND DATA ANALYSIS DURING ADAPTIVE SITE MANAGEMENT

Management decision periods 2 through 4 require information in the form of quantitative data from a monitoring program and subsequent data analysis. For example, MDP2 involves the following key questions: (1) is the remedy meeting the performance standards (as set forth in the ROD or other binding documents), (2) are the operational expectations of the remedy being met (whether cost or other parameters that the remedial project manager and remediation team have set), and (3) is the remedial goal being met. Affirmative responses to these questions lead to "response complete" and eventually to MDP4, whereas negative responses lead to MDP3. Chapter 3 discusses in detail the parameters that should be measured to answer these questions, given the existing remedy and remedial goal, and several innovative monitoring techniques.

MDP3 allows for the remedy to be optimized, modified, or replaced entirely. Optimization of an existing remedy leads back to the "design process: remedy and monitoring" box, as denoted by the dashed line in Figure S-1. For those remedies that do not perform appropriately even after optimization, wholesale replacement may be required, necessitating a return to the "select remedy" box. Although a wide array of tools can help evaluate whether an additional remedial action or change is warranted once the point of diminishing returns has been reached, relatively simple graphical tools, described in Chapter 3, can be used. For example, in the case of groundwater contamination, contaminant concentration within the source area can be plotted over time; the need for a change may be evident when the slope of the line tangent to the performance curve approaches zero (the so-called asymptote) but the concentration remains above the site-specific remedial action goal. Such plots can also make it clear when continued operation of the existing remedy may incur substantial per unit costs with relatively little improvement in mass removal. These graphical techniques can also be utilized prior to initial remedy selection if enough information exists on the performance curves typical of certain treatment schemes. However, for most remedies, characteristic remedy curves and the predictive models that might generate such curves are not yet available. The following conclusions and recommendations from Chapter 3 concern the monitoring and data analysis aspects of ASM.

Plots of mass removal and/or concentration versus time or cost (or other metrics depending on the remedy) are objective and transparent tools for illustrating remedial effectiveness that should trigger when to either modify or optimize the existing remedy or to change the remedy. Such graphs should be used after remedy selection to address MDP2 and MDP3. Graphical representations should serve both to enhance stakeholder understanding of the options and to make better decisions about implementing or modifying remedies. At individual sites under investigation, the Navy, in consultation with all stakeholders, should select a unit cost for the continued operation of the remedial action, above which the existing remedy is no longer considered a tenable option.

The Navy should collect and analyze data to develop and validate predictive models of remedy performance. The remedy selection process could be made more quantitative and transparent with the provision of design guidance, charts, and models that summarize technology applications and predict their performance in different environmental settings.

Uncertainties in hydrogeological data, contaminant concentrations, and rates of remediation should be explicitly recognized in the development and application of performance plots. There are many sources of uncertainty in estimating the mass or risk reduction achieved by any remediation scheme. When sufficient site data are available, statistical methods can be used to estimate error or confidence bands on the performance plots. Site monitoring plans should be developed to ensure that the collected data serve to reduce uncertainty.

A concerted effort should be made to increase monitoring program effectiveness (and to reduce costs) by optimizing the selection of monitoring points, incorporating field analytics and innovative data collection technologies such as direct push, and adopting dynamic work plans and adaptive sampling and analysis techniques. Real-time *in situ* monitoring technologies should also be considered as those technologies mature. These techniques enhance the collection of information upon which ASM decision making is based. DoD should continue to support and foster research in chemical, physical, and biological techniques that would provide more rapid and adaptive approaches for monitoring remedy effectiveness.

EVALUATION AND EXPERIMENTATION

An essential feature of ASM is that it allows for a change in remedy—where the chosen approach is falling short of cleanup goals—that takes into account information about other potentially more effective remedies collected during evaluation and experimentation. Information from laboratory studies, on- or off-site pilot-scale activities, expert panel evaluations, literature reviews, or experience from other federal or private sector sites should be assessed on a regular basis to determine if a more effective remedy applicable to the site of concern exists. The evaluation and experimentation track of ASM specifically accommodates potential problems with remedy effectiveness by improving the understanding of the site (site conceptual model) and suggesting ways to enhance the performance of the existing remedy or guide the selection of an alternative remedy. Evaluation and experimentation can open up new opportunities to remediate and manage sites more effectively even when problems are not imminent. A more external benefit of evaluation and experimentation is that it can create an expanded database on the performance of remedial technologies. For a responsible party like the Navy that has a large number of hazardous waste sites, the external benefits of investing in learning (i.e., using what is learned in one place at other sites and in future decisions) can be substantial.

This parallel track is critical to overcoming the stalemate encountered at many sites where cleanup goals cannot be achieved. However, for this to succeed, potentially responsible parties in particular, and the federal government more generally, must make evaluation and experimentation an integral part of their overall remedial program. This feature of ASM differentiates it from the recent Navy guidance on remedy optimization, which does not explicitly specify the need for such activities.

There are numerous mechanisms for undertaking evaluation and experimentation at individual sites, and for obtaining relevant information and data externally (discussed in detail in Chapter 4). Some involve DoD agreements with U.S. Environmental Protection Agency (EPA) laboratories or offices, extramural grants with academic institutions or other non-governmental groups, or collaborative activities such as those conducted through the Remediation Technology Development Forum, a joint effort between EPA and private industry. Adoption of ASM would encourage the Navy to build stronger networks within the scientific and engineering communities in order to stay abreast of new technological developments that might prove applicable to future cleanup scenarios.

Although time will be required to test ideas and new technologies prior to a full-scale implementation, ASM should not be used as an argument for delaying important decisions while extensive analysis takes place. In fact, a hallmark of adaptive management is that more certain and sometimes simple actions are taken immediately while information is gathered about potentially more effective but less certain technologies. While evaluation and experimentation take place, the temporary inability to meet performance standards or other regulatory requirements should not be used as a basis for notices of deficiency or enforcement action. The following conclusions and recommendations address the role of evaluation and experimentation in ASM.

Evaluation and experimentation are integral to adaptive site management and should occur concurrently with remedy implementation. Improved understanding of a site through evaluation and experimentation can reduce the amount of uncertainty associated with the risk estimate, suggest ways to enhance the performance of the existing remedy, and help guide the selection of an alternative in case the remedy is ineffective in meeting cleanup goals. Employing evaluation and experimentation is most important for remedies likely to reach an asymptote prior to meeting the remedial goal, for sites with intractable contamination such as DNAPLs and metals, and where containment or institutional controls are used.

DoD should expand its programs that focus on developing and testing innovative remedial technologies and monitoring techniques. The lack of such research will result in DoD and others not having the new tools that can improve remedial programs and reduce long-term fiscal liabilities. Responsible federal agencies should collaborate closely with researchers in the public and private sectors to ensure that remedial project managers are trained and knowledgeable on innovative technologies that might be used to replace existing ineffective remedies.

Congress should make sure there are funds available to support the evaluation and experimentation track of adaptive site management. Although significant research efforts have been underway, unless the federal government provides new resources, only slow progress will be made toward finding cost-effective methods of reducing contaminant levels and meeting cleanup goals. Federal government support is needed to fill the gap left as a result of the lack of market incentives to develop innovative hazardous waste cleanup technologies.

Resource, timing, regulatory, and socioeconomic obstacles need to be overcome in order to fully adopt evaluation and experimentation as a component of ASM. Such obstacles include a lack of funds in federal cleanup programs beyond those needed to implement the chosen remedy; site manager perceptions that the results from research yield answers over time scales that are too slow to prove useful in optimizing existing remedies or in making informed decisions about when to replace a remedy; and the increasing use of containment and institutional controls, which has discouraged additional investment in the development of new remediation technologies.

INNOVATIVE TECHNOLOGIES

Chapter 5 reviews a variety of innovative technologies the Navy might consider during initial remedy selection, as replacements for existing remedies that have proved to be unsuccessful, or as additions to current remedies to better achieve cleanup goals or reduce cleanup time. Because the Navy identified its most pressing current problems as solvents and metals in soil and groundwater and sediment contamination, the focus is on these types of contamination and applicable remedial technologies, including *in situ* chemical oxidation, thermal treatment, permeable reactive barriers, enhanced bioremediation, technologies for treating contamination by inorganics, and several sediment management techniques.

Although all the technologies have their place, there is no clearly superior single remedy that can address even a small fraction of the Navy's contamination problems. In general, for the innovative technologies reviewed, there is a lack of refined evaluation procedures and peer-reviewed literature on their cost and performance—partly because their development is vendor-driven—making it impossible to fully evaluate their success or efficacy. Thus, further testing of innovative or new experimental technologies at selected sites is needed, both for site-specific application and if the results are likely to improve cleanup activities at other sites. In the evaluation of remedial options and technologies, the full life cycle of a technology and the management and disposition of all residuals that may be generated by the technology should be considered.

Optimization of existing remedies is also discussed in Chapter 5. Optimization can be as simple as ensuring that system components are still appropriate and are operating at design efficiency. Formal mathematical optimization can be used to evaluate well configuration and pumping rates in pump-and-treat or soil–vapor extraction systems for potential cost savings. In the course of taking such action, the degree of protectiveness of the remedial action at the site must not be reduced. More detailed instruction for site managers on how to optimize various remedial systems is required, because existing information in DoD guidance manuals is presented in very general terms and can be used only by persons who are already quite technically knowledgeable in the remediation field. In general, the reevaluation of the current remedy design for possible optimization should be a routine part of adaptive site management. The conclusions and recommendations below pertain to specific innovative technologies.

Site-specific analyses of the effectiveness of source removal technologies, including *in situ* chemical oxidation, thermal treatment, and enhanced bioremediation, are needed to better guide and justify remedy selection. Controlled field demonstrations are needed to evaluate the benefits (e.g., to groundwater quality) derived from partial mass removal from source zones and the compatibility of some technologies with natural attenuation. This should help in the determination of whether enough source mass can be removed to warrant the expense of implementing the technology.

Permeable reactive barriers can effectively treat a limited number of groundwater pollutants under well-defined hydrogeologic conditions. These pollutants include perchloroethylene, trichloroethylene, *cis*-dichloroethylene, and perhaps chromium (VI). The technology has been applied in the field for only seven years, so data on long-term performance are limited. Hydraulic capture remains a key issue in determining effectiveness, and the long-term integrity of these systems is unknown.

Because metal contaminants cannot be destroyed and their behavior and speciation are strongly coupled to site-specific conditions, remediation approaches for metal contaminants remain a challenge. Given that metals are frequently reported contaminants of concern at Navy sites, the Navy should devote resources to accelerate the development and field-scale testing of cost-effective technologies for mitigating risks from metal contaminants.

Presently, the only options that are routinely available for managing contaminated sediment include natural attenuation, capping either in situ or after dredged material removal, and dredging with disposal in confined disposal facilities or in upland landfills. Dredged material treatment options are under development and may be commercially available and viable in the future.

Treatment trains for the remediation of many contaminated sites are an important component of adaptive site management. Most sites are contaminated with multiple contaminants that may require different treatment processes. A common treatment train is source control in conjunction with monitored natural attenuation. This approach must be implemented with caution as certain source removal technologies can disrupt microbial metabolism via redox changes, removal of primary substrates, and creation of inhibitory conditions.

LONG-TERM STEWARDSHIP

Because many remedies today utilize containment and institutional controls rather than treatment of the contaminant source, residual contamination is expected to remain at these sites such that unrestricted use of soil, groundwater, and surface water will not be permitted. The activities needed to maintain such remedies collectively are called long-term stewardship, which is an integral part of ASM. Long-term stewardship starts when remediation, disposal, or stabilization is complete or, in the case of long-term remedial actions such as groundwater treatment, when the remedy is shown to be functioning properly. MDP4 during long-term stewardship provides the opportunity to ask the following questions: is there residual contamination that prevents unrestricted use, and is there a reason to revisit the remedy? The second of these questions represents a significant departure from the way many responsible parties usually conduct long-term stewardship. As shown in Figure S-1, this might lead to the replacement of containment or institutional controls with a more active remedial system. The motivation for asking this question is to be able to reach site closeout, which is not possible unless contamination is permanently reduced to levels that allow for unrestricted land use.

There are other reasons that site managers should reconsider remedies in place during long-term stewardship. Considerable cost savings may be possible if a new technology can alleviate the need for continual monitoring and/or maintenance. Also, there are substantial economic benefits to returning a site to unrestricted land uses. In the case of contaminants such as recalcitrant organic compounds, heavy metals, and radionuclides, land use controls may be required for hundreds or thousands of years. Over this timeframe, the cost and viability of land use controls is highly uncertain. Rarely is the complete future life-cycle cost of the original remedy compared to the life-cycle cost of implementing a new remedy. Clearly, an accurate assessment of the life-cycle costs is important to implementation of ASM.

The five-year review process of Superfund is the typical vehicle for assessing the protectiveness of remedies during long-term stewardship. However, as discussed in Chapter 6, the five-year review process currently does not support reconsideration of remedies during long-term stewardship if they are maintaining protectiveness of human health and the environment. Adoption of ASM would require expanding the scope of the five-year review process to include MDP4 and the basic elements of long-term stewardship—stewards, operations, public information, public participation, research, and information systems. This includes considering whether there are newly available technologies that could expeditiously lead to site closeout; if there were a more effective remedy available, the user would cycle back through the previous parts of ASM (see Figure S-1). Other improvements in the five-year review process are also suggested, particularly with regard to the lack of adequate public involvement in long-term stewardship, the performance and capability of the stewards, and the adequacy of funding for long-term stewardship.

During long-term stewardship, the remedy should be reconsidered as part of the five-year review, even if it is currently protective of human health and the environment. Because of changing conditions and the development of new technologies, there may be opportunities to achieve remedial goals for less money or in less time or achieve more aggressive remedial goals for the same money and time. Thus, it may be possible to replace land use controls with treatment remedies that will achieve unrestricted use and lead to site closeout. Only if unrestricted use levels are attained can the military and other agencies permanently remove sites from federal stewardship. The benefits of achieving site closeout include not only cost savings from reduced long-term operation and maintenance costs, but also increased taxes and minimization of potential future legal liability.

A government-wide policy for long-term stewardship (also known as long-term management) at federal sites is needed. Because all federal agencies with environmental restoration programs face this issue, ideally the Administration should convene an interagency task force for this purpose. This activity is needed to legitimize the basic elements of long-term stewardship and the expenditure of resources on these elements. As part of this effort, it will be important to develop a life-cycle cost estimating technique and appropriate discounting methods that reflect the timeframes for which long-term stewardship will be needed.

OVERALL CONCLUSIONS AND RECOMMENDATIONS

Adaptive management approaches are now being used by a number of public and private organizations to improve the quality of their operations and decisions. Like the domains of natural resource and business management where the principles of adaptive management have been applied, site cleanup planning, remediation, and stewardship involve significant uncertainty in system response. Despite these similarities, to the committee's knowledge adaptive management has never been formally used for hazardous waste cleanup. There is strong support for adaptive approaches already present in recent federal guidance on monitoring and remediation. For example, recently developed guidance for the Navy and Air Force recommends close scrutiny of existing remedies and monitoring data and informal optimization of remedies. The Navy guidance calls for an alternative strategy when a plot of cumulative mass removed versus time exhibits "an asymptotic condition" prior to attaining the cleanup goal. ASM goes further to suggest how to interpret the monitoring data, when to consider using new technologies, and how to reach site closure for all types of sites. The inclusion of evaluation and experimentation within ASM affords a way to manage uncertainty while moving forward with the cleanup process because conventional remedies can be implemented first while additional information is gained on innovative but more risky technologies.

The Navy and other federal agencies should adopt adaptive site management. The underlying statutes on hazardous waste management are consistent with adaptive site management, and existing regulatory guidance could be modified to be so. All the mechanisms for changing and modifying selected remedies—formal remedy amendments, RCRA permit modifications, contingency records of decision, five-year reviews, technical infeasibility waivers, and optimization studies, among others—can be encompassed by ASM. The Navy is currently drafting policy that will require periodic reviews of remedies, as prescribed by recent Navy guidance on optimization. Because ASM is broader in scope, it will be necessary for the federal agencies to develop guidance to further define the management decision periods that are inherent to ASM.

The responsible federal agency should solicit public involvement during each of the four management decision periods of ASM. Changes to the remedy, the remedial goals, and future land use should be issued only after consideration of public comments. Although many individual guidance documents mention public involvement, there is no coherent public involvement process described in existing guidance or practiced in the field *after* remedy selection. As part of the Restoration Advisory Board rule development process, DoD should work with regulators, public representatives, and other stakeholders to develop a menu of options for involving the public in the long-term oversight of cleanup programs at facilities where remedies or long-term stewardship activities are continuing.

Full-scale ASM that includes public participation during each decision period should be targeted to the more complex and high-risk sites where projected large costs are at stake. ASM is particularly appropriate for sites with multiple or recalcitrant contaminants and multiple stressors and heterogeneous hydrogeology because progress at such sites is likely to have stalled prior to reaching cleanup goals. Prior to widespread adoption, the Navy should consider pilot testing ASM at a limited number of high-risk, complex sites to allow Navy managers to better understand any transactional costs and delays that may accompany ASM implementation.